Dust Production of Comet 21P/Giacobini-Zinner using Broadband Photometry

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Abstract

Presented here are results from photometric analysis on broadband images taken of Comet 21P/Giacobini-Zinner from May 24, 2011 to October 24, 2011. As the parent body of the Draconids, a meteor shower known for outbursting, 21P was studied for its dust production activity, *Afρ,* focusing on how it changes with heliocentric distance. An expected increase in dust production with a decrease in heliocentric distance was observed. The comet went from heliocentric distance of 3.05 AU to 1.77 AU during the observed time that corresponded to an apparent magnitude of 19.61 to 15.72 and *Afρ* of 16.48 cm to 284.17 cm. These values can be extrapolated to estimate a peak *Afρ* value at perihelion of 3824 cm. The images were obtained using a 0.5-meter f/8.1 Ritchey-Chrétien telescope located in Mayhill, New Mexico.

Introduction

Comet 21P/Giacobini-Zinner is a Jupiter family comet that was discovered in December of 1900 by the French astronomer Michel Giacobini and rediscovered in 1913 two orbits later by German astronomer Ernst Zinner (Pittichova et al. 2008). 21P is approximately 2 km in diameter, has a perihelion of 1.03 AU, and is the parent of the Draconids, a meteor shower known to undergo dramatic outbursts. In 1933 and 1946, up to 10,000 meteors per hour were reported for the Draconids (Jenniskens 2006); and 2011 saw a minor Draconid outburst (Vaubaillon et al. 2011). In order to better constrain meteor stream forecasts for the Draconids, 21P was monitored to determine the heliocentric distance variation of *Afρ* (A'Hearn et al. 1984), a quantity that describes the dust production rate and one that is used in cometary dust ejection models.

Afρ is a quantity independent of an observer's site and equipment, of the geometrical arrangement of the comet in the Solar System, or wavelength of images taken. It has been shown that the *Afρ* results obtained from both CCD filter photometry and spectrophotometry agree (Schleicher and Bair 2011). Typical values of *Afρ* are anywhere from 5 cm to 5000 cm and are majorly affected by the size of the comet and its distance from the Sun. The quantity is calculated from the apparent magnitude and is an aperture-independent quantity for comets having a $1/\rho$ fall-off (ρ being the distance from the nucleus to the edge of the aperture) in their brightness profile, standard for comets in a quiescent state. This study presents multi-aperture photometry of 21P for its pre-perihelion passage from 3.05 AU to 1.77 AU. Multi-aperture photometry gives further insights into the comet as variation seen in *Afρ* for various *ρ's* implies the comet's activity is increasing or decreasing; often caused by changing heliocentric distance or an outburst. Observing 21P over a range of heliocentric distances also allowed a determination of the slope of how *Afρ* changes with distance to the Sun, also included in this report.

Comet Giacobini-Zinner has received attention in the past as it has passed close to Earth in several of its apparitions and become as bright as 7th magnitude. It was the first comet to have measurements made *in situ.* Comet 21P was visited by ICE (International Cometary Explorer) in 1985 to study the interaction of the cometary atmosphere with the flowing solar-wind plasma (von Rosenvinge et al. 1986). It is a carbon-depleted comet (Lara et al. 2003), and most studies show that it peaks in gas and dust production pre-perihelion, specifically in two well-studied passages; 1985 and 1998 (McFadden et al. 1987, Lara et al. 2003). The gas emission of 21P has been studied in-depth (Landaberry et al. 1991, Ellis and Neff 2000); however there has been considerably less analysis on the dust emission. 21P's dust production during its previous two apparitions were studied by Pittichova et al. (2008) and Lara et al. (2005) and will be compared and discussed to the results found in this report.

Theory

The quantity *Afρ* is based off A'Hearn et al.'s 1984 study and designed to describe how dusty or inactive comets are. Often comet outbursts are characterized by sharp increase in *Afρ* which is explicitly the albedo of the grains *(A),* multiplied by the filling factor of the grains *(f),* and the nucleocentric distance *(ρ).* It is calculated using the Earth-comet distance, (*Δ)*, nucleocentric distance (the distance from the comet's nucleus to the edge of the aperture being used for photometry), the flux of the Sun at 1 AU in the same filter used to image the comet, F_{SOL}, and the observed flux from the comet found using the apparent magnitude, F_{COM}. Explicitly the filling factor (*f*) is $N\rho\sigma / \pi\rho^2$ where σ is the cross section of a single grain.

$$Af\rho = \frac{(2\Delta R)^2}{\rho}\frac{F_{COM}}{F_{SOL}} \quad \text{[Equation 1]}$$

$$\rho = \tan(1.12838 * \frac{5}{206{,}265})\Delta \quad \text{[Equation 2]}$$

$$F_{COM} = 10^{\frac{M_{app}}{-2.512}} \quad \text{[Equation 3]}$$

$$F_{SOL} = 10^{\frac{-27.15}{-2.512}} \quad \text{[Equation 4]}$$

Δ and *ρ* are in cm, but *R* is in AU. M_{APP} is -27.15 when finding F_{SOL}, which corresponds to the Sun's magnitude in the R filter. In Equation 2, *5* accounts for the radius of a 10x10 arcsecond aperture, which is converted to radians (1 arcsecond =1/206,265 radian), and *1.12838* is a correction factor as the true aperture is not a square, but a circle whose area is equivalent to the square used by FoCAS.

FoCAs (FOtometria Con AStrometrica or Photometry with Astrometrica) (Roig et al. 2011), the reduction software used in this study to perform multi-aperture photometry, has set apertures of 10"x10", 20"x20'" 30"x30", 40"x40" and so on. *Afρ* was derived for each aperture as this tells us information about how the dust falls off with distance from the nucleus. *Afρ* is designed to be independent of aperture size for comets with the canonical 1/*ρ* falloff in surface brightness and hence dust profile (Jewitt and Meech 1987). It is, however, dependent on the solar phase angle, for which a correction was applied as discussed below. Deviations from the 1/*ρ* falloff can be attributed to a significant increase or decrease in dust production from seasonal changes, different active regions being stimulated, grain fading, among other effects (Schleicher et al 1998). When new particles are lifted off the surface of the comet, they often remain in the inner coma for days or months, resulting in a higher *Afρ* value at lower *ρ's* before the particles disperse and the comet goes back to a quiescent state. This implies that smaller apertures encase younger, newer material released from the nucleus that has not yet dissipated through the comet tail (Schleicher 2009). For comet 21P, it was sufficient to use apparent magnitudes found with a 10x10 arcsecond aperture as 21P was not a diffuse enough comet - 10x10 arcseconds encapsulated the dust .

Method

Images of 21P were obtained in the Johnson R-filter from May 24, 2011 until October 24, 2011 (3.05 to 1.77 AU heliocentric distance). The comet was not observed below 2 airmasses. The equipment used was a 0.5-meter f/8.1 Ritchey-Chrétien telescope on a German equatorial mount with an Apogee 16M CCD camera located in the mountains of southern New Mexico (Mayhill, NM), and operated remotely from Marshall Space Flight Center. Standard bias and dark subtraction and flat-field reduction were performed on all data.

21P was imaged up to several dozen times per night, though only a few images per night were selected for analysis after examining the images for background stars, cosmic rays, image artifacts or other problems that would affect the photometry. The chosen images had photometry analysis performed with Astrometrica (Raab 2005) and FoCAs. Astrometrica, using the Carlsberg Meridian Catalog 14 (CMC-14), produces a log file of the astrometry and photometry of all reference stars as well as the object, which must be manually chosen. The log file produced by Astrometrica is read by FoCAs, then FoCAs determines the centroid of the object to perform its multi-aperture photometry. The value of the background of the image is found as the median of the whole image, not with concentric circles around the object itself (as in other photometric software), which minimizes contamination from the tail of the comet. The results from each image analyzed per night were then averaged together to give an apparent magnitude per night.

Phase Dependence

In order to see true variation in the dust production over time, a correction for solar phase angle must be applied. Phase affects a solar system body in different ways based on the composition/grains. As comets often do not have consistent out gassing, it is difficult to measure this effect and a standard correction procedure does not exist.

Figure 1 shows the curve used for phase correction applied to all data presented here. It was found using a technique which is a splice of two curves (personal communication with D.G. Schleicher), one using data from comet Halley at small phase angles (Schleicher et al. 1998), and the other based on the Henyey-Greenstein function (Schleicher and Bair 2011, Marcus 2007). All *Afρ* values were normalized to opposition (0°). This implies that all data in this report are extrapolated and the values of *Afρ* are higher than those originally measured. Consequently, values of *Afρ* before phase correction (denoted *A(θ)fρ)*, and after phase correction are both presented in this report. As phase correction for comets is an ongoing work, the original data may be revised accordingly in the future.

Results

Over the five months 21P was imaged, May-24-2011 to October-24-2011, the comet went from an apparent magnitude of 19.61 to 15.72, corresponding to an absolute magnitude of 15.06 to 12.13 (Figures 2 and 3). This spanned a heliocentric distance of 3.05 AU to 1.77 AU. The magnitudes presented here are averages found from analyzing several images per night. The average is weighted over the night according to the signal to noise ratio of the comet in each image. Errors in the graphs correspond to the average photometric errors after performing a fit to CMC-14 catalog magnitudes. The magnitudes, and thus the *Afρ* graphs presented here, were determined with a 10x10 arcsecond aperture, which corresponds to ρ of 9100 +/- 500 km (as 21P's Geocentric distance, Δ, varies).

The magnitudes presented in Figures 2 and 3 correspond to *Afρ* of 16.48 cm to 284.17 cm. Table 2 catalogs the results throughout the entire run of observations of 21P. The second to last column is *Afρ* before phase angle correction is applied, which we call *A(θ)fρ* because of the phase dependence on the albedo. The last column is *Afρ* after the phase angle correction has been applied. This is presented in graph form in Figure 4. *A(θ)fρ* results (before correction for phase) are presented as the grey data, and the data after *Afρ* has been corrected for phase is presented in black. As discussed above, with decreasing heliocentric distance, phase correction extrapolates *Afρ*.

Dust production of 21P followed a logarithmic slope (γ) of -4.468 with respect to heliocentric distance. ($Af\rho \propto R_{\text{¤}}^{\gamma}$) The slope permits the extrapolation of the data out to the perihelion (1.038 AU) of 21P, to an *Afρ* of 3824 cm. The *Afρ* and γ of a comet are two of the main descriptors of its dust production. There were no significant outbursts during this time. There was a slight increase in brightness around 2.8 AU for several nights, seen as a slight increase in *Afρ* which could correspond to a small outburst in 21P. However, 21P was passing through a dense star-field during this time, which could have affected the photometry. As typical comet outbursts have an immediate brightening of several magnitudes, contamination by field stars appears likely.

Dust production was measured with 3 apertures (ρ). The change in the coma and tail of 21P with decreasing heliocentric distance can be clearly seen by examination of the surface brightness profile (*log*(*Afρ) vs log(ρ)*). This is reflected in Table 1. When 21P is 3.05 AU from the Sun, it is nearly a point source. However by 1.77 AU from the Sun, 21P has grown a pronounced coma which extends into larger apertures. As the values of *Afρ* with smaller apertures are still greater than those at larger apertures, this indicates that there is new dust coming off the nucleus of 21P and the comet is not in a quiescent state. The new dust does not immediately dissipate throughout the coma and tail but can take days or month to do so, therefore after new dust is released from the nucleus the dust production tends to have higher rates with smaller apertures. The values determined using the 9000 km aperture (10x10 arcseconds) yielded the peak *Afρ* values, and are presented in Figures 2,3,4 and Table 2 in this paper.

Discussion

The results presented here are in rough agreement with Pittichova et al's 2008 results, covering 21P's previous apparition in 2005 (Pittichova et al. 2008). They were also looking at R-band images and found 21P had an apparent magnitude of 15.91 corresponding to an *A(θ)fρ* (non-phase corrected) of 130.55 cm when the comet was 1.76 AU from the Sun and an apparent magnitude of 17.05 corresponding to *A(θ)fρ of* 82.07 cm when the comet was 2.32 AU. Also it should be noted that these are post-perihelion values as 21P has exhibited different dust emission characteristics between its pre and post perihelion passages (Lara et al. 2003, Schleicher et al. 1987). The analysis also compares favorably to Lara et al.'s 2003 results from 21P's 1998 apparition. Their peak *A(θ)fρ* (non-phase corrected) value was 1010 cm in the red continuum at 1.05 AU. It was imaged at perihelion (1.03 AU) with an *A(θ)fρ* of 649 cm. These values are lower than the theoretical value at perihelion that this study found through extrapolation, but one needs to keep in mind that Lara et al's values are not corrected for phase and correcting for phase would increase their *A(θ)fρ* values. A third similar study by Schleicher et al. (1987) studied 21P at smaller heliocentric distances. They found a peak *Afρ* value of 416 cm at 1.087 AU, which is pre-perihelion similar to when Lara et al. (2003) found their peak value.

Pittichova et al (2008) derived a slope of -2.04 regarding how *Afρ* changes with heliocentric distance. This is not as steep as the γ of -4.468 found with the data in this study, though their data was taken of 21P post-perihelion. A pre-perihelion value, perhaps more compatible to compare with the value derived here, was found of -2.08 +/- 0.15 by A'Hearn et al (1995). The value found by A'Hearn et al used 13 sets of observations when 21P was between 1.507 AU and 1.053 AU, a smaller heliocentric distance than observations taken for this study.

Conclusions

21P/Giacobini-Zinner behaved as expected over the five month of observations: it shows increased dust production with decreasing heliocentric distance and no outbursting. At the beginning of the observation run on May 24, 2011, when 21P was 3.05 AU from the Sun, it was found to have an apparent magnitude of 19.61 equaling an absolute magnitude of 15.06. This corresponds to an *Afρ* of 16.48 cm. At the end of the observation run, on October 24, 2011, 21P was 1.77 AU from the Sun and was found to have an apparent magnitude of 15.72 equaling an absolute magnitude of 12.13. This corresponds to an *Afρ* of 284.17 cm. The *Afρ* values in this report were corrected for phase as the albedo of the comet is known to have a strong dependence of the solar phase angle.

21P is an important Solar System body, being the parent of the Draconids, a meteor shower known for dramatic outbursts. This meteor stream has been modeled extensively and two parameters that are helpful in modeling are the dust production at perihelion, and the slope of the dust production with heliocentric distance. This study found a slope (γ) of -4.468 and an extrapolation of the data gives an *Afρ* of 3824 cm at perihelion.

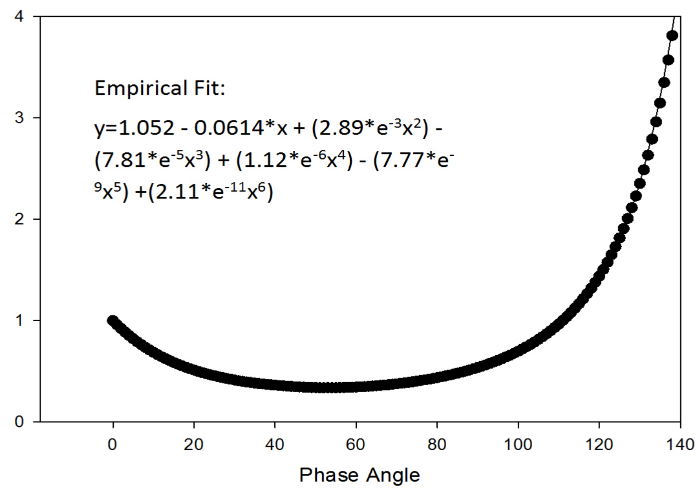
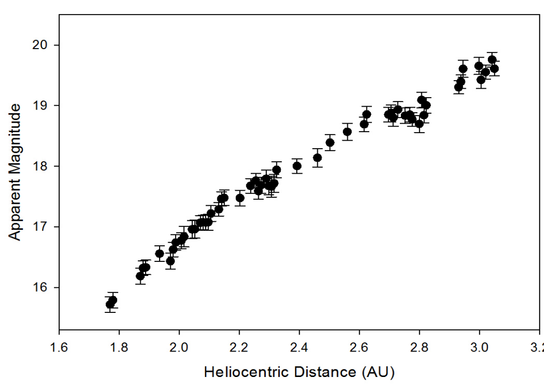
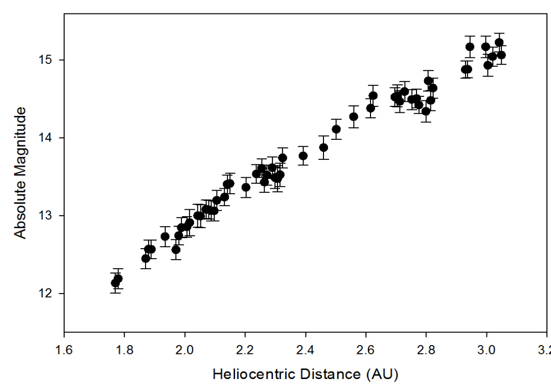


Figure 1: Normalization curve for phase angle correction used in this report.





Figures 2 (left) & 3 (right): Apparent (left) and absolute (right) magnitude of Comet 21P from May 24 to October 24, 2011, corresponding to a heliocentric distance of 3.05 AU to 1.77 AU.

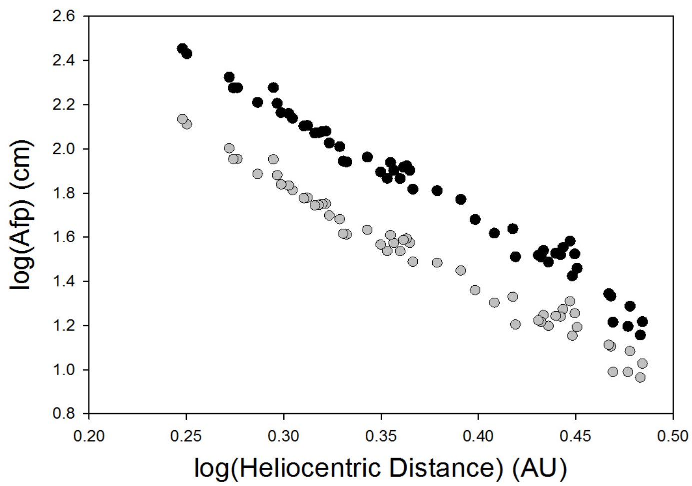


Figure 4: Dust production of Comet 21P from May 24 to October 24, 2011. Grey points represent *A(θ)fρ*, dust production found before correcting for solar phase angle, and black points represent *Afρ*, dust production after the solar phase angle correction has been applied.

ρ (km)	9000	18000	27000
Afρ at 3.04 AU (cm)	16.48	11.07	7.64
Afρ at 2.29 AU (cm)	82.43	63.61	49.72
Afρ at 1.77 AU (cm)	284.17	262.51	211.85

Table 1: Dust production of 21P for three aperture sizes and various heliocentric distances.

Date	Heliocentric Distance (AU)	Geocentric Distance (AU)	Phase Angle Θ(°)	ρ (*10^3 km)	Apparent Magnitude	Absolute Magnitude	A(Θ)fρ (cm)	Afρ[a] (cm)
24-5-2011	3.0489	2.1545	10.6008	8.82	19.609	15.063	10.65	16.48
25-5-2011	3.0415	2.1449	10.754	8.78	19.757	15.226	9.21	14.32
28-5-2011	3.01973	2.137	11.2397	8.74	19.55	15.044	10.91	17.24
30-5-2011	3.0045	2.1299	11.6122	8.72	19.424	14.932	12.11	19.37
31-5-2011	2.9972	2.1266	11.8137	8.70	19.654	15.169	9.75	15.68
7-6-2011	2.9447	2.1112	13.3134	8.64	19.601	15.169	9.76	16.41
8-6-2011	2.9374	2.1099	13.5641	8.63	19.311	14.881	12.72	21.52
9-6-2011	2.9299	2.1089	13.7922	8.63	19.005	14.861	12.95	22.05
23-6-2011	2.8223	2.1145	17.1601	8.65	19.005	14.639	15.58	28.77
25-6-2011	2.8068	2.1181	17.6201	8.67	19.093	14.733	14.24	26.55
26-5-2011	2.7989	2.1201	17.8501	8.68	18.697	14.340	20.38	38.18
29-6-2011	2.7755	2.1269	18.5301	8.70	18.771	14.422	18.78	35.68
30-6-2011	2.7677	2.1292	18.7501	8.71	18.852	14.505	17.36	33.13
2-7-2011	2.7519	2.1348	19.1875	8.74	18.834	14.491	17.50	33.67
5-7-2011	2.7282	2.1469	19.8056	8.78	18.934	14.594	15.77	30.71
7-7-2011	2.7123	2.15005	20.2001	8.80	18.800	14.467	17.66	34.63
8-7-2011	2.7043	2.15336	20.3919	8.81	18.872	14.541	16.45	32.38
9-7-2011	2.6963	2.15675	20.5799	8.83	18.851	14.522	16.70	32.97
18-7-2011	2.6239	2.18996	22.0998	8.96	18.856	14.5423	16.00	43.44
19-7-2011	2.6158	2.1939	22.2491	8.89	18.536	14.224	21.35	43.40
26-7-2011	2.5593	2.2215	23.1635	9.09	18.568	14.270	20.10	41.48
2-8-2011	2.502	2.2493	23.9121	9.20	18.389	14.109	22.90	47.82
7-8-2011	2.46	2.268	24.2248	9.28	18.138	13.875	28.09	58.97
15-8-2011	2.392	2.298	24.8382	9.40	18.003	13.767	30.47	64.58
23-8-2011	2.3241	2.3232	25.1371	9.51	17.940	13.741	30.81	64.60
24-8-2011	2.31558	2.32605	25.1625	9.52	17.719	13.525	37.49	79.85
25-8-2011	2.30695	2.32882	25.1852	9.54	17.672	13.488	39.26	83.64
26-8-2011	2.2983	2.3315	25.2053	9.55	17.793	13.616	38.64	82.42
27-8-2011	2.2896	2.3341	25.2229	9.56	17.212	13.039	34.26	73.26
29-8-2011	2.2723	2.3391	25.2507	9.57	17.686	13.519	37.44	79.85
30-8-2011	2.2636	2.3414	25.261	9.58	17.589	13.429	40.64	86.69
31-8-2011	2.2549	2.3437	25.269	9.59	17.762	13.608	34.46	73.52
2-9-2011	2.2374	2.3479	25.2783	9.61	17.675	13.534	36.79	78.59
6-9-2011	2.2024	2.3552	25.2718	9.64	17.475	13.362	42.95	91.63
12-9-2011	2.1494	2.3632	25.2069	9.67	17.479	13.412	40.90	87.16
13-9-2011	2.1405	2.3642	25.1904	9.67	17.461	13.402	41.26	87.91
14-9-2011	2.13166	2.3651	25.1725	9.68	17.288	13.237	47.99	102.23
17-9-2011	2.10569	2.36702	25.1117	9.68	17.219	13.194	49.87	106.13
18-9-2011	2.09677	2.36747	25.0884	9.69	17.077	13.060	56.39	119.96
19-9-2011	2.0878	2.3678	25.0638	9.69	17.069	13.062	56.29	119.71
20-9-2011	2.07889	2.36807	25.038	9.69	17.074	13.075	55.61	118.21
21-9-2011	2.06993	2.3682	25.011	9.69	17.068	13.079	55.43	117.79
23-9-2011	2.0519	2.3682	24.9539	9.69	16.961	12.992	60.05	127.49

24-9-2011	2.043	2.3679	24.9237	9.69	16.957	12.998	59.73	126.76
27-9-2011	2.0159	2.3667	24.8277	9.68	16.838	12.909	64.87	137.45
28-9-2011	2.0069	2.3661	24.794	9.68	16.773	12.855	68.21	144.45
30-9-2011	1.9889	2.3645	24.7243	9.68	16.741	12.844	68.93	145.82
1-10-2011	1.9798	2.3635	24.6885	9.67	16.626	12.741	75.87	160.42
2-10-2011	1.9708	2.3625	24.6521	9.67	16.434	12.559	89.60	189.33
6-10-2011	1.9345	2.357	24.5018	9.64	16.557	12.729	76.94	162.21
11-10-2011	1.8889	2.3478	24.3074	9.61	16.331	12.565	89.90	188.93
12-10-2011	1.8797	2.3456	24.2681	9.60	16.32	12.567	89.84	188.70
13-10-2011	1.87059	2.34326	24.23	9.59	16.186	12.446	100.50	210.96
23-10-2011	1.77902	2.31492	23.85	9.47	15.79	12.19	129.10	269.37
24-10-2011	1.76985	2.31154	23.81	9.46	15.718	12.131	136.28	284.17

[a]Phase corrected to 0° (opposition) using a composite curve by D.G. Schleicher (Schleicher and Bair 2011).

Table 2: Summary of results for the entire observation run of 21P/Giacobini-Zinner.

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